Optimizing Agricultural Water for Food, the Environment and Urban Use

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Irrigated agriculture remains the primary consumptive use of water in the United States; however, population growth, environmental needs and changing societal values are driving a reallocation of water away from agriculture. It is projected that, by 2030, 33 million additional people will be living in the western United States, requiring approximately 30 billion more gallons of water for consumption per year (Western Governors' Association, 2006). In much of the semi-arid areas of the world, new water resources will be in limited supply, particularly if remaining watersheds, aquifers and streams are protected from additional withdrawals for crop or livestock production. Water continues to move from farms to cities, and the social, economic and environmental results of these water transfers are important and sometimes are not anticipated or well understood. As a consequence, growth and subsequent water conflicts are occurring in agricultural areas in the West and across the nation, where key water resources are often fragile and scarce, as pointed out in the Bureau of Reclamation's Water 2025 Report (Figure 1). As this trend advances, there is legitimate concern about our ability to meet projected food demands under reduced irrigation water supplies.

From a global perspective, modern agriculture has its roots in the so-called "green revolution" that began with introduction of high-yielding rice and wheat cultivars in the 1960s. It is less well recognized that the "blue revolution" in irrigation expansion took place alongside the development of shorter-statured high-yielding cultivars (Figure 2). Global expansion of irrigated lands appears to have leveled off and major irrigated regions in the western United States are under considerable stress to reduce water consumption to meet environmental, energy and municipal water demands. The promise of "more crop per drop" makes for a catchy slogan, but we need to carefully examine the implications of reduced irrigation water on food supplies and producer risk exposure as we plan adaptation strategies.

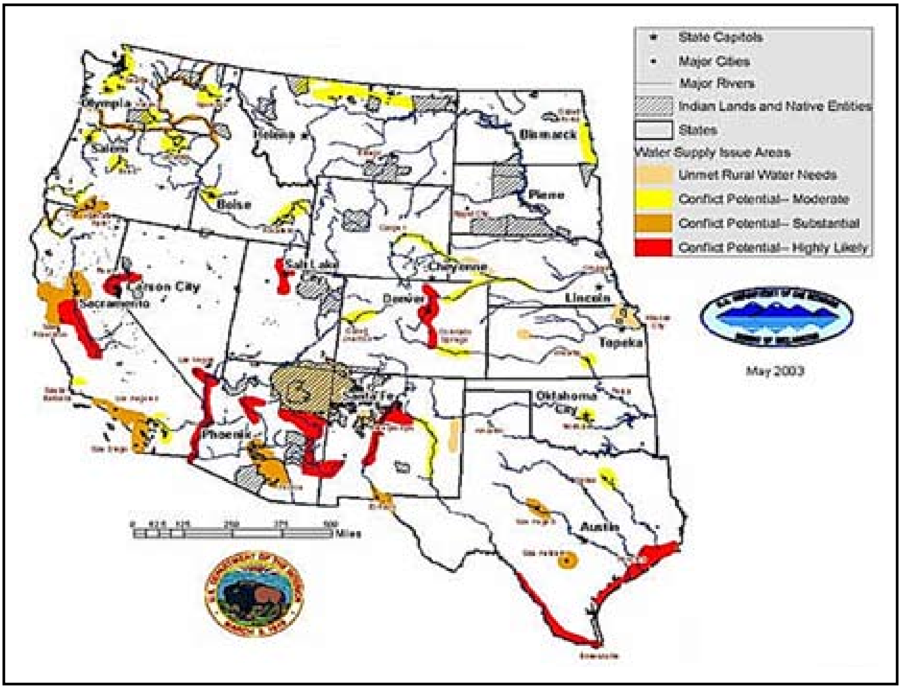

Figure 1. Potential water-supply crises by 2025 in the western United States (DOI, 2005).
(Areas where existing supplies are not adequate to meet water demands for people, for farms, and for the environment.)

Freshwater ecosystems, already impaired in many basins, will be further threatened under projected climate forecasts, requiring more water for environmental flows, not less. Endangered-species concerns, such as those over longfin smelt in the San Francisco Bay and Delta[1], will potentially disrupt agricultural diversions at critical times during the cropping season, when producers are most at risk. Agriculture currently consumes over 70% of total freshwater used by humanity, competing with the energy sector, which comes in a distant second. Even so, energy and other users can easily out-spend agriculture for water. It is important to recognize that while only 15% of total US crop acres are irrigated, approximately 40% of total crop value comes from these acres, including many of the economically important grain, vegetable and fruit crops.

In simple terms, optimizing agricultural water use involves growing more food while reducing agriculture's environmental footprint. Agricultural water managers must address competing demands of urban development, energy and ecosystems. Perhaps what is needed is a new approach that couples agriculture and the environment as an integrated

[1]http://www.fws.gov/cno/press/release.cfm?rid=375.

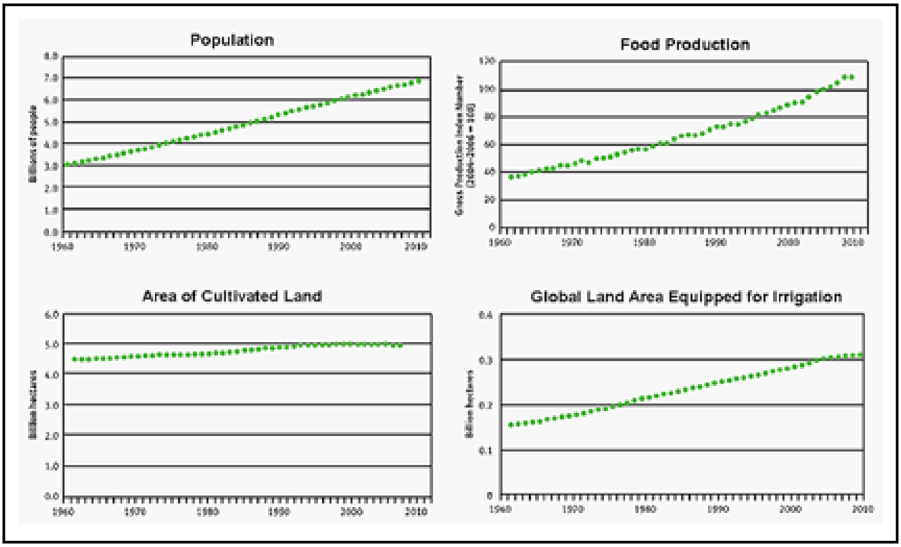

Figure 2. Trends in global food systems (from Beddington *et al.*, 2011)

system, rather than separating these sectors as distinct problems or sectors. In this article I will use case studies as examples that touch my home state of Colorado to examine these points and prospects for new approaches—the Ogallala Aquifer and the Colorado River Basin. I'll argue that both the problem and solutions to global water problems lie within agriculture.

Case Example 1: Ogallala Aquifer

Groundwater and surface water have historically been thought of as distinct sources in terms of public perception and legal framework. Unlike surface-water supplies where flooding, depletion, and contamination problems are readily apparent, groundwater problems may take years or decades to manifest themselves into recognizable concerns. This has historically led to a lax attitude regarding groundwater, even though systematic depletion of aquifers such as the Ogallala has long been documented. However, through national and regional assessments like the USGS NAWQA programs, there is a growing recognition of problems associated with falling groundwater tables, increased drinking water contamination, and a better understanding of the linkage between ground- and surface-water resources that has resource managers struggling to develop cost-effective solutions (USGS, 2004).

The High Plains Aquifer underlies a 111-million acre area (174,000 sq mi) of the eight Great Plains states of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas and Wyoming. It is one of largest freshwater aquifer systems in the world and is the most intensively used aquifer in the United States, providing 30% of the total withdrawals from all aquifers for irrigation (*Maupin and Barber*, 2005). The High Plains agricultural economy runs on water from the Ogallala. The crop-, livestock- and meatprocessing sectors are the backbone of the regional economy and provide many jobs. Irrigated crops provide feed for livestock, which are part of a large meat-packing industry in the region. An estimated 15 million cattle and 4.25 million hogs are raised annually over the aquifer (Waskom *et al.*, 2006). Approximately 23% of the cropland overlying the Ogallala is irrigated, accounting for 94% of the total groundwater use on the High Plains (Sophocleous, 2010). Irrigated acreage on the High Plains Aquifer increased rapidly from 1940 to 1980, but did not change greatly from 1980 to 2002, stabilizing at approximately 14 million acres.

The Ogallala formation underlies 80% of the High Plains and is the principle geologic unit of the High Plains Aquifer. An estimated 165,000 wells currently pump from the aquifer (Waskom *et al.*, 2006). The aquifer is recharged very slowly in the semi-arid environment of the Great Plains, creating essentially a nonrenewable resource in many areas. Recharge rates vary from 0.024 inches per year in Texas upwards to 6 inches per year in parts of Kansas and Nebraska. Substantial pumping over the past 40 years has led to water-level declines of up to 150 feet and 50% of the saturated thickness in localized areas of the aquifer (Table 1). Although the rate of decline has slowed in recent years, the downward trend continues in many areas, threatening the long-term viability of an irrigation-based economy.

Table 1. Water level changes in the High Plains Aquifer, predevelopment to 2009 (adapted from McGuire, 2011).

State	Area-weighted average water-level change (feet)	Change in water in storage (million acre-feet)
Colorado	–13.2	–19.4
Kansas	–22.8	–64.7
Nebraska	–0.9	–16.6
New Mexico	–15.1	–11.4
Oklahoma	–12.3	–13.0
S. Dakota	0	–0.5
Texas	–36.7	–145
Wyoming	–0.4	–2.6
Total	–14.0	–273

Falke *et al.* (2011) investigated linkages between groundwater pumping from the High Plains Aquifer and stream fish habitat loss, and found most refuge pool habitats dried completely or lost more than half their volume, disconnecting from other pools by late summer. Under conservative modeling scenarios, they predicted that maintaining current water-table levels and refuge pools for fishes would require a 75% reduction in groundwater pumping, which is not economically or politically feasible. Given widespread streamflow declines, ecological futures are bleak for stream fishes in the western Great Plains under current groundwater-pumping regimes.

Because water-level declines in the High Plains Aquifer have been large, they have substantially decreased the saturated thickness of the aquifer in some areas. Reduced well capacity in most areas means lost crop production, as both irrigated acres and crop yields decline. A reduced well yield means that irrigation is less effective at meeting crop evapotranspiration (ET) during peak crop-water-use time periods. Not only do yields decline with aquifer depletions, but yields also become more variable. The lost income and increased variability in income threatens the local economy and the future viability of the agricultural operations depending upon products grown on Ogallala water.

Currently, both Colorado and Nebraska are looking for ways to reduce pumping and to decommission wells to meet the compact compliance terms of the lawsuit on the Republican River. Given current commodity prices, producers are highly interested in new hybrids and varieties that might have greater yield potential or stability under reduced irrigation allocations. Producer response to reduced water availability on the High Plains includes:

- Rotational and split cropping with dryland crops or fallowed land
- Limited, deficit and partial season irrigation
- Shift to sunflowers, sorghum, wheat, forage crops
- Higher level of irrigation scheduling and water management
- Reduced tillage to maintain surface residue, decrease evaporation and increase precipitation capture
- Re-nozzle sprinklers and remove pivot end guns
- Use of EQIP, CREP and other farm programs to retire lands and reduce pumping

Case Example 2: Colorado River Basin

The Colorado River Basin is one of the most critical sources of water in the Southwest, spanning seven US states and Mexico. This river's remarkable reach includes providing water to more than 30 million people, irrigating nearly four million acres of agricultural land, and serving as the limiting resource for at least 15 Native American tribes, seven National Wildlife Refuges, four National Recreation Areas, five National Parks in the United States and a Biosphere Reserve in Mexico. The river's energy powers more than 4,200 MW of electrical capacity to households and industry. However, the river and its ecosystems are at risk as increasing water demands and climate change are poised to collide with a fully appropriated basin.

Agriculture in the Colorado River Basin is driven by irrigation, with about 4 million acres of land receiving irrigation from the river system, representing about 15% of all crop receipts and 13% of all livestock in the United States. The vulnerabilities that climate change portends for the basin are serious, but we should probably recognize that severe weather, population growth and the attendant municipal, energy, industry and recreational water needs already stress irrigated agriculture in this Basin. The agricultural industry in the Basin as a whole is heavily dominated by livestock production and attendant feed and forage needs. Subsequently, the irrigated crops grown are dominated by grass hay, alfalfa, and feed grains in the Upper Basin, whereas the value of vegetable and fruit crops becomes increasingly significant as you move downstream towards Arizona and California.

Historically, the Colorado River drainage had 42 native fish species, including 30 endemic species found in no other river system. Of these endemic species, 4 are extinct, 12 are listed as endangered, and 4 are threatened. Approximately 60% of the fish species found in the basin are found only in the Colorado River Basin. Flow needs to sustain native fishes have not been fully quantified, but are very valuable from economic and ecological standpoints. For the Native Americans who live in the Basin, most of their water rights are senior to the more traditional rights held by agriculture and the cities. Some of the tribal reserved water rights remain to be quantified; creating uncertainty about how much of the river will be allocated to the tribes. Mexico also has a thriving agriculture that depends on this river. In addition, the Basin supports a vibrant recreational economy in the southwest United States, with the Grand Canyon at its heart.

Particular areas in the Colorado River Basin (most notably lower central Arizona) have already seen significant reductions in irrigated agriculture as land near growing urban areas is converted to housing or dried up for urban water. The distribution of farms is trending toward many small, irrigated holdings that produce smaller shares of household income, and fewer large farms that support the majority of irrigated cropping. It is unclear how this might influence future conservation and water-management practices or how it might influence future water transactions. This basin has been slower to adopt sprinkler and drip-irrigation techniques because of the particular needs and economics of the dominant production systems. Adaptation to societal pressure for more water for recreation, environment and municipal use has largely been through market transactions that dry up agriculture, either temporarily or permanently.

Understanding Crop-Water Needs and Opportunities to Optimize

While the public widely perceives that agriculture can easily be managed to conserve water, crop growth and yield are tightly coupled to ET. In general, 70% to 80% of the total crop consumptive water use is via transpiration from the plant canopy. There is a direct relationship between the amount of ET and crop biomass because plant stomata must be open for a plant to assimilate carbon. When plant stomata are open, water vapor is lost to the atmosphere. In this way, 99% of the water that is taken up by the plant is returned to the atmosphere in the form of water vapor.

The amount of ET and the relative percent of consumptive use evaporation vs. transpiration are dependent upon the following factors:

- Crop type (cool v. warm season and maturity length)
- Percent of canopy cover (stage of development and plant population)
- Irrigation system and frequency of application
- Residue cover (*e.g.*, mulch/tillage system)
- Soil moisture status

When evaluating agricultural water-conservation improvements, it is important to distinguish between practices that lead to improved irrigation application efficiency and those that lead to reduced consumptive use. Irrigation-water-use efficiency is defined as the ratio of water applied compared to water consumed by a crop (*i.e.*, ET). Increasing irrigation efficiency is likely to reduce losses from deep percolation and runoff (thereby altering historical return flow patterns), but it may or may not materially affect the amount of water consumed by the plant. Much of the water lost to these inefficiencies will return to the river or groundwater system for use by downstream diverters.

In most cases, upgrading irrigation systems increases water-use efficiency, but does not necessarily reduce consumptive use. Reducing consumptively used water can result when one or more of the following occurs:

- Irrigated acres are decreased
- Crop selection is changed from a summer crop to a cool-season crop
- Crop selection is changed to one with a shorter growing season
- Deficit irrigation is practiced, applying some amount less than full ET over the growing season
- Evaporative losses from the field surface are reduced as a result of conservation tillage, mulching, and or drip irrigation

Most of the difference in consumptive use between crops can be explained by canopy cover, season of active growth and length of growing season. Crops grown during the cool season, such as winter wheat, are subject to lower atmospheric demand and, thus, lower ET rates. Reducing the length of crop-growing days also can reduce irrigation demands. These differences in season-long consumptive use as a result of growing day length or growing period are illustrated in the ET data for one location in Table 2.

Table 2. Growing season and cumulative ET for various crops at Holyoke, Colorado (adapted from USDA-NRCS Colorado Irrigation Guide; accessed online May 2012).

Crop	Growing season (Average dates)	Growing season (Days)	Seasonal ET (inches/season)
Alfalfa	3/20–10/10	204	35.2
Sugarbeet	4/25–10/10	168	29.9
Corn/grain	5/5–10/5	153	25.4
Soybean	5/25–10/5	133	16.4
Spring grains	4/1–7/25	115	15.2
Dry bean	6/1–9/5	96	18.7

Agricultural Water Conservation Techniques that Reduce Crop Consumptive Use and Nonproductive Consumptive Losses

Current state water laws generally allow irrigators flexibility in crop types, irrigation timing, methods, and application rates. If properly managed, crop consumptive use or nonproductive consumptive losses may be reduced by the following practices:

- Lower water-use cropping systems
- Acreage fallowing
- Shorter-season/cool-season crops
- Limited/deficit irrigation
- Removal of pivot end guns and reduce acres
- Ditch piping and lining (reducing evaporation, ET, and seepage)
- Crop-residue management and mulching
- Phreatophyte[2] control

We currently have many technologies for increasing the effective use of water, but we will need new mechanisms and greater incentives for optimizing agricultural water use. Promising approaches include:

- Developing new crop varieties and cropping systems
- Sharing water between agriculture, cities, and the environment
- Streamlining water markets
- Transitioning to rainfed and limited irrigation strategies
- Modernizing water-distribution networks
- Developing economic tools to help producers determine highest economic use of their available water
- Linking life-cycle of energy and water inputs to production systems
- Developing agricultural systems that are resilient to uncertain water supplies and drought; and
- Improving agricultural water-management institutions, policies and organizations.

Additionally, our catchments—particularly forest and rangeland—must be actively managed to sustain necessary water resources and preserve functioning ecosystems and watersheds.

Blum (2009) argues that crop breeding for water-limiting conditions leads to reduced yield and reduced drought resistance as we are fundamentally limited by the biochemistry of photosynthesis. The notion of more crop per drop sounds good, but it may be misleading. Water-use efficiency (WUE) is an old irrigation concept that has moved into

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[2]A deeply rooted plant that obtains a significant portion of its water from the saturated phreatic zone or the capillary fringe above the phreatic zone.

the crop-improvement vocabulary. Transpiration efficiency is what breeders should be most concerned about: the amount of water transpired per unit of CO_2 fixed. The goal should be to maximize the CO_2 fixed per unit area under drought or water-limited or full-irrigation conditions. Effective use of water (EUW) implies maximum soil-moisture capture and uptake for transpiration—a more important target for yield improvement in water-limited environments. It is well known that moisture stress at reproductive stages is most yield limiting. Given that limited- or deficit-irrigation scenarios are a likely future in many basins, one significant problem is supplying water at later critical growth stages. Deficient irrigation portends higher levels of producer management and higher levels of risk.

The full promise of biotechnology for significantly greater crop-water productivity appears to lie somewhere in the future and may depend upon some fundamental restructuring of plant physiology and morphology. Significant genomic innovation for WUE has been relatively slow to develop, whereas our water problems are immediate. Our agricultural productivity depends upon creating new mechanisms for increasing food productivity using less water—we need new solutions in the next few decades to sustain our productivity. Many of the technological advances needed for water optimization in agriculture are already well in hand; for example, more-efficient irrigation systems, soil, water and evapotranspiration monitoring and information systems, water reuse, and rain-fed cropping systems have been designed to capture and optimize precipitation efficiency. It is often the institutional, economic and social barriers that constrain producer adoption and further implementation.

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